Reprinted from
Electroencephalography and Clinical Neurophysiology
Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

EEG IN SIMULATED STRESSES OF SPACE FLIGHT WITH SPECIAL REFERENCE TO PROBLEMS OF VIBRATION[1]

W. R. ADEY, W. D. WINTERS, R. T. KADO AND M. R. DELUCCHI

Space Biology Laboratory, Brain Research Institute, University of California at Los Angeles and Veterans Administration Hospitals, Long Beach and Los Angeles, Calif. (U.S.A.)

(Received for publication: July 19, 1962)

The many and singular problems confronting man's entry into space lie virtually entirely in the realm of speculation at this time. The brief periods of weightlessness and other stresses to which man has been exposed so far in current programs of orbital flight appear not to have been associated with critical disruptions either in physiological systems or in psychic performance capability. It is obvious that these experiences in the space environment may well have been too short to reveal functional trends, which, if continued, might vitally affect judgment and performance capability, and even survival.

A number of physical stresses of great potential importance to man in the space environment may be expected to be accompanied by functional changes in the central nervous system. For example, the combined stresses of noise, acceleration and vibration encountered in attainment of orbital flight and during re-entry, though of relatively brief duration by comparison with the states of profoundly modified sensory influx associated with weightlessness, may be associated with massive afferent volleys in vestibular and proprioceptive modalities, and with disturbances of both gross and regional aspects of the cerebral circulation. The degree to which vibration may occur during launch and re-entry will obviously vary with different vehicles and with different flight configurations, but its occurrence as a factor capable of modifying perceptual accuracy has already been mentioned in U.S. manned space flight (Shepard 1961; Glenn 1962). The effects of various forms of vestibular stimulation, such as prolonged slow rotation, likely to occur in a space vehicle, have already received considerable attention (Graybiel *et al.* 1961). The effects of vestibular stimulation on EEG activity has been studied by Molnar (1961), but the effects of vibration on the EEG have only been reported briefly (Adey *et al.* 1961a), and the elucidation of its sensory receptor mechanisms and central responsive systems has remained unknown.

This study has been undertaken to examine the effects of vibration of the whole body on EEG records from surface and deep brain structures, as part of a program to monitor directly brain functions in space flight, insofar as it may be possible with current techniques. This would appear to present both an opportunity and a challenge. The challenge would appear to lie principally, but not solely, in the development of instrumentation appropriate to the physical stresses involved. Here, as in other areas, the neurophysiologist must develop an awareness of the importance of the philosophy of engineering systems. His experiments are no longer conducted in isolation, either from simultaneous experiments in other body systems, or from the life support, data acquisition and telemetry systems with which his equipment must mate efficiently and reliably (Henry 1961). Here, as never before, the biomedical team is required to examine the whole man, and on the basis of this monitoring, to make judgments about present status and, in particular, about future performance and prospects for survival.

Our studies in the past three years have ranged widely through the problems of instrumentation of EEG for space flight. We have developed a series of amplifiers with miniaturized and microminiaturized construction as well as developing data acquisition systems and initiating a variety of computational techniques

[1] Presented at American Electroencephalographic Society Meeting, Atlantic City, June, 1962 in Symposium "EEG in Relation to Space Travel".

in EEG analysis. The experiments began with cats, and have ranged progressively through monkeys and chimpanzees to man. We have simulated the accelerational and vibrational stresses associated with booster flight and re-entry, and studied the effects of isolation and sensory reduction in simulated 14-day flights and in other ways (Adey 1961a, b; 1962a, b; Adey *et al.* 1960, 1961a, b, 1962; Kado and Adey 1961; Lindsley *et al.* 1961; Winters *et al.* 1962). These studies have included examination of steroid excretion in relation to these stresses.

MATERIAL AND METHODS

Four pig-tailed macaque monkeys (*Macaca nemestrina*), ranging in body weight from 4.5–6.8 kg were implanted with bipolar electrodes in the midbrain reticular formation, lateral geniculate body, nucleus centrum medianum thalami, amygdala, hippocampal formation and occipital cortex, using a stereotaxic atlas prepared in this laboratory. In many instances, electrode placements were in bilaterally symmetrical sites. The depth electrodes were made from 29-gauge stainless steel tubing insulated with several coats of epoxy varnish. These tubes were inserted stereotaxically in pairs separated from each other by a distance of 2.0 mm. The recording dipole was formed between the tips of the two tubes, which were bared from a distance of 1.0 mm from the tip.

Prior to shaking tests, all four animals were subjected to centrifuging at the centrifuge facility of the University of Southern California,

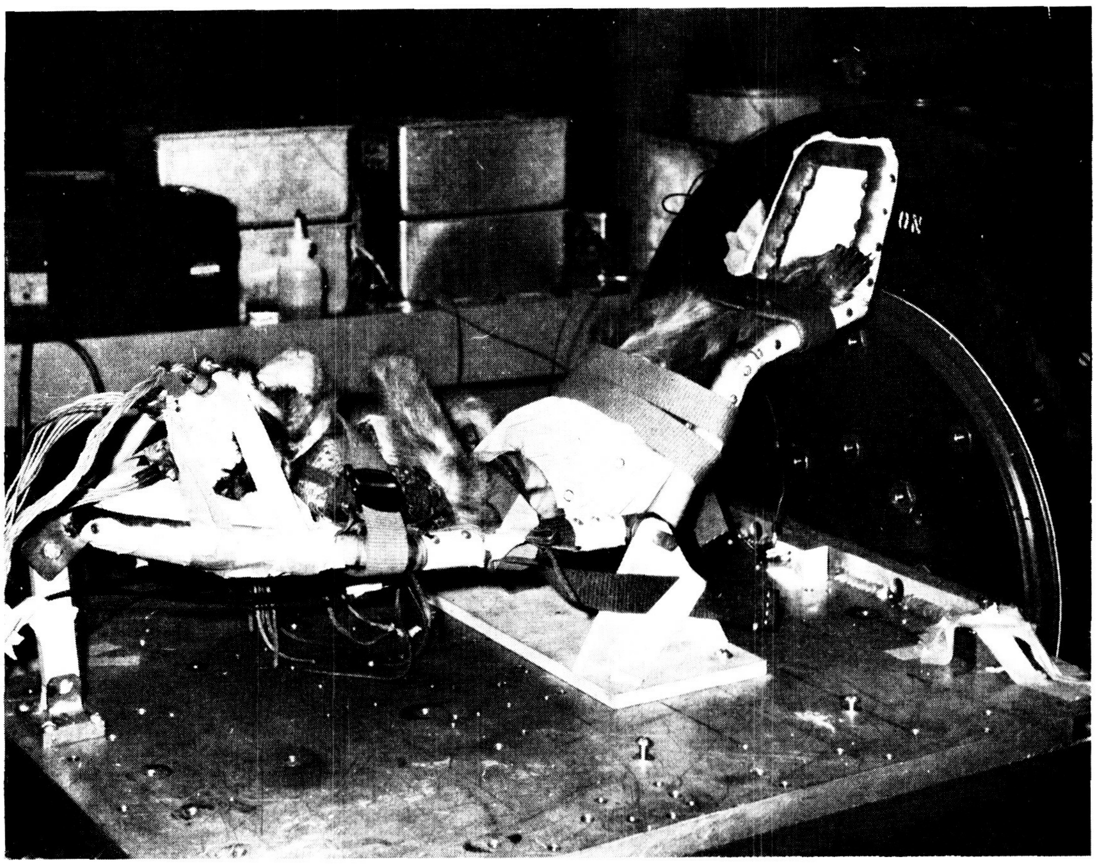

Fig. 1
Monkey on shaker. The animal's supporting couch is bolted to the heavy aluminum plate of the transducer, and the axis of acceleration can be changed to test effects in horizontal and vertical planes. Dummy electrodes mounted for flux leakage test adjacent to flux gap in transducer can be seen at front right edge of the shaker table, attached with masking tape. Accelerometers are attached to head and torso.

Electroenceph. clin. Neurophysiol., **1963,** *15*: 305–320

reaching a maximum acceleration of 8–10 *G* in both transverse and longitudinal axes. Centrifuge tests were combined with vibration to provide a picture of the effects of these combined stresses on the ultimate picture of histological damage, as well as evidence concerning the mechanical stability of the cranial attachment of the implant and associated lead systems to the pre-amplifiers. Techniques, already described in detail elsewhere (Adey *et al.* 1960, 1961a) have been developed to minimize the appearance of electromechanical artifacts in association with the shaking. Briefly, extremely rigid attachments were secured by a clamp-locking technique at the animals' head between male and female components of the plug system. A special anti-static cable (Microdot Corporation "Mininoise"[1]), with metallic powder deposited on each side of its metallic braid in close contiguity with over- and underlying layers of plastic, has proved effective in eliminating virtually all artifacts associated with mechanical deformation of connecting cables.

Stainless steel wires were sutured subcutaneously in the midaxillary lines at the level of the fifth rib for recording the EKG. These leads gave satisfactory records under most conditions, but were susceptible to movement artifacts.

Shaking in the present series of tests was performed at the laboratories of Douglas Aircraft, Inc., Santa Monica, Calif., using electronically operated shaking transducers (Fig. 1). Each animal was shaken in three successive planes at right angles over a spectrum from 5–40 c/sec, in continuous sweeps of ascending and descending frequency. The acceleration was maintained at 0.25-inch (6-mm) double amplitude (peak-to-peak deflection) from 5–13 c/sec, and then changed to a constant acceleration of 2 *G* peak-to-peak to a maximum frequency of 40 c/sec. This constitutes a standard technique in vibration testing. Constant amplitude vibration is used at low frequencies to avoid large excursions (up to several inches) to produce a 2-*G* peak acceleration at these frequencies. It is apparent that at a constant 2-*G* acceleration, the amplitude of the deflection decreases with increasing frequency. The monkey was strapped to a special chair attached to the shaker table.

[1] Microdot Corporation, 220 Pasadena Avenue, South Pasadena, Calif. (U.S.A.).

Piezoelectric accelerometers (Brush) were attached to the table and to the animals' torso and head. Special tests of the stability of the lead system and for artifacts arising from flux leakage from the shaker transducer will be described below.

Primary data acquisition involved both magnetic tape and conventional EEG recording. The tape recording system is a narrow-band FM multiplex system, using IRIG subcarrier oscillators, and with the capability for recording as many as fourteen channels of information on a single tape track. IRIG (Inter Range Instrumentation Group) standards are established under U.S. Military Specification T26985 for FM–FM stations receiving, decoding and recording telemetered data. This system has proved ideal for field use, particularly in the ruggedness of its components and its electrical stability. In addition to EEG data, EKG, EMG, behavioral programming details, animal's noises and voice protocol were all recorded with appropriate "flagging" to facilitate subsequent epoch selection, data reduction and computation. Simultaneous paper-written EEG records were obtained on Grass EEG instruments (Model 6) with eight or sixteen available channels.

All four animals were trained in an oddity discrimination task as the basis for a food reward. The discrimination involved three projected symbols, arranged in a horizontal line, and presented in a random sequence of squares, triangles, circles, etc. The presentation involved one symbol always being odd with respect to the other two, and with the odd symbol appearing at any one of the three projection screens. Initiation of a feeding session was marked by appearance of a green light on the test panel, and successive presentations were made at random successive intervals of 10–50 sec. The monkey secured a food pellet by pressure on the panel on which the odd symbol was projected. Special automated behavioral test equipment has been developed to present a feeding session at selected times, and its operation is fully compatible with EEG recording.

Further details of microminiaturized preamplifiers developed for these studies will be presented below. Histological sections of the brain of one animal (sacrificed to secure records from a recently dead animal) have been prepared by serial frozen section and stained by the Nissl and Weil methods.

RESULTS

Since the validity of any inferences concerning phenomena of electrical "driving" appearing at the shaker frequency in the course of shaking must rest entirely on the elimination of ambiguity from electrically or mechanically induced artifacts, the controls in this type of study must be exceedingly rigorous. They are, therefore, presented here as necessary antecedents to an account of the normal concomitants of the shaking process.

A. *Control studies*

1. *Use of dummy electrodes.* Prior to shaking of the monkeys, careful checks were made to exclude the introduction of electrical artifacts into the recording system. The transducer resembles a conventional loudspeaker. A cylindrical "voice" coil, carrying alternating currents at the shaking frequency, oscillates within the field of a large permanent magnet. Two principal sources of interference are likely to be encountered. Leakage of magnetic fields from the voice-coil of the transducer or movement of connecting leads in a flux field from the steady magnetic field of the transducer's magnet system may both induce electrical artifacts at the shaking rate. Deformation of plastic-covered leads may also induce an electrostatic charge on the wire.

Magnetic induction artifacts were carefully checked by placing a set of 10 kohms resistors attached to a socket identical with those on the animals' heads adjacent to the gap between the armature and pole pieces of the transducer and carrying out a full spectral sweep with the shaker. The resistors were wired in such a fashion as to form closed loops between appropriate connector pins for optimum induced voltage effects. The sweep did not produce artifacts, probably in large measure due to a "hum-bucking" arrangement incorporated in the transducer design. The dummy electrodes were also placed in the position of the animals' heads on the recording couch, without evidence of artifact. Steps taken to eliminate electrostatic charges on the cable are described above.

2. *EEG records during deep anesthesia and after death.* The gamut of changes occurring during shaking in the conscious animal will be described below. First, however, it may be emphasized that great care was taken to eliminate from consideration records from leads in which EEG changes persisted essentially unaltered in deep barbiturate anesthesia or death. This problem occurred in less than 10 per cent of all leads in the four animals tested.

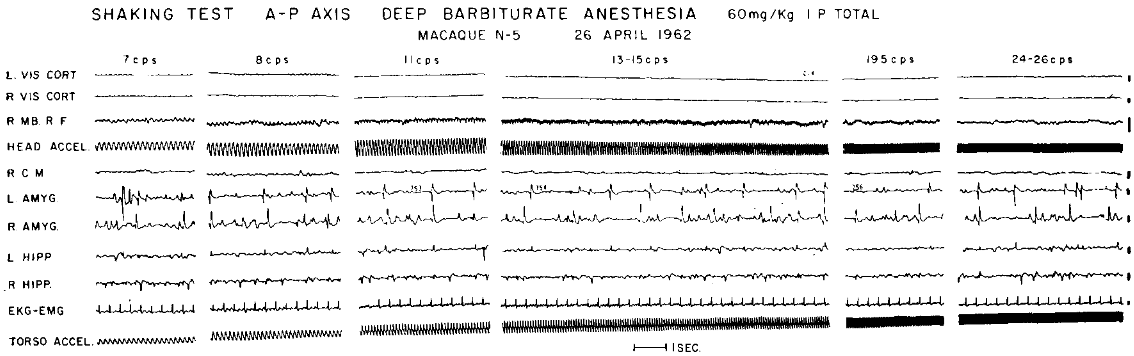

Fig. 2

Representative portions of EEG records from macaque monkey during shaking under deep pentobarbital anesthesia (60 mg/kg i.p.). Shaking was at 0.25 inch double amplitude from 5–13 c/sec and at constant 2 *G* peak-to-peak from 13–40 c/sec. No appreciable driving of EEG rhythms can be seen (see text). Abbreviations indicate following channels from above down: left and right visual cortical leads, right midbrain reticular formation, head accelerometer, right nucleus centrum medianum, left and right amygdalae, left and right hippocampi, electrocardiograph-trunk electromyograph lead, and torso accelerometer. Calibration 100 μV.

Typical records in pentobarbital anesthesia (60 mg/kg) are shown in Fig. 2. Representative sections of record at shaking frequencies from 7–26 c/sec are shown. It will be seen that visual cortical leads were essentially flat. There was a very low amplitude rhythmic discharge at shaker frequencies around 7 and 8 c/sec in leads from midbrain reticular formation and centrum medianum, but this disappeared at higher frequencies. This may constitute a residual physiological excitation. Amygdaloid and hippocampal leads showed only irregular high amplitude spikes, with no evidence of "driving" at shaker frequencies. These findings may be compared with those in the same animal in the wakeful state (Fig. 4).

In one instance, the anesthetic state was terminated by intracardiac injection of potassium chloride, which produced cardiac arrest. In the dead animal, the findings confirmed the absence of any "driving" from virtually all cortical and subcortical leads. Those few in which driving persisted after death were presumably due to a microphonic problem in the lead or electrode system and have been eliminated from further consideration.

3. *Photic driving tests.* Prior to vibration tests, photic stimulation was performed with a Grass photostimulator over the same spectrum of frequencies (5–40 c/sec) as in the shaking tests. It was found that good driving occurred in the visual cortex (R.VIS.CORT., Fig. 3), particularly at frequencies around 10 c/sec, and slightly in the midbrain reticular formation (L.MB.RF.). Other cortical and subcortical zones showed almost no driving. These findings contrast sharply with those during shaking presented below.

To test the possibility that the driving detected during shaking might arise from concurrent photic stimulation with eyes open, some shaking tests were performed with the monkey blindfolded. It was found that the driving persisted without alteration in amount or distribution in the blindfolded animal.

B. *EEG changes during shaking tests*

In agreement with earlier tests (Adey *et al.* 1961a), intermittent driving of brain rhythms occurred at the shaking frequency. This driving was maximal at frequencies between 9 and 15 c/sec.

With sustained shaking at 15 c/sec (2 *G* peak-to-peak), the intermittent character of the driving is obvious (Fig. 4). It was found in this and other animals that this driving was best sustained in visual cortical leads (screws over posterior occipital cortex). It was very prominent in the midbrain reticular formation, and was considerable in the nucleus centrum medianum. In rhinencephalic cortex, there was obvious driving in hippocampal leads, and a small amount in the amygdala.

A characteristic aspect of these induced changes was the dissociation of the bursts of

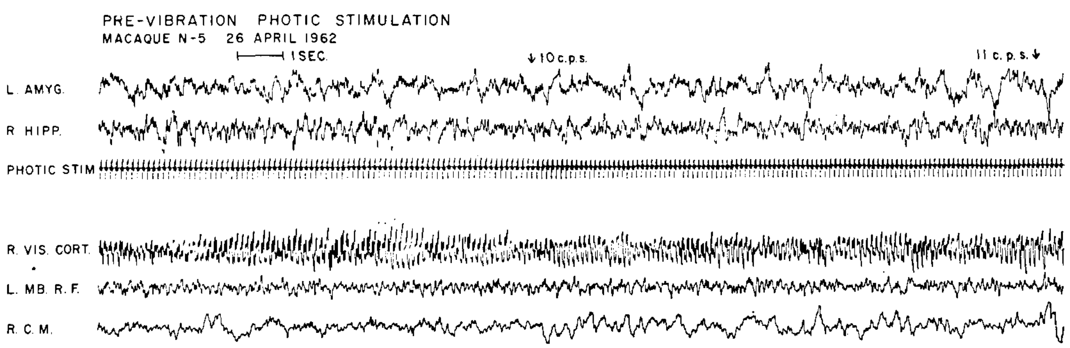

Fig. 3

From same monkey as in Fig. 2, showing strong driving in visual cortex (R.VIS.CORT.) at flash rates around 10/sec, and moderate driving in midbrain reticular formation (L.MB.R.F.), but relatively little in amygdala (L.AMYG.), hippocampus (R.HIPP.) or nucleus centrum medianum (R.C.M.). Calibration 100 μV.

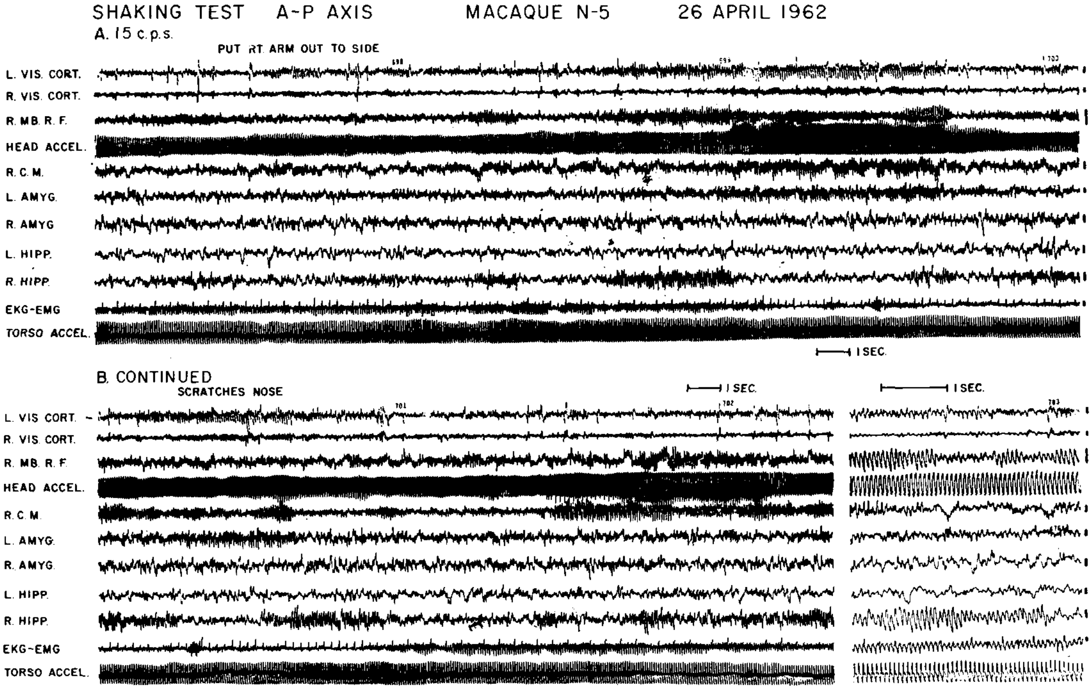

Fig. 4

From same monkey as in Fig. 2 and 3, showing effects of sustained shaking at 15 c/sec. There is widespread intermittent driving in cortical and subcortical structures. Lead pattern as in Fig. 2. Calibration 100 μV.

driven waves in simultaneous records from different brain regions, as, for example, in the times at which bursts of high amplitude driving occurred in the midbrain reticular formation and the visual cortex (Fig. 4, *A*). Additionally, an asymmetry was frequently noted between homologous regions of the two hemispheres, and is in agreement with findings in our previous shaking tests (Adey *et al.* 1961a). Moreover, physically adjacent regions, such as the midbrain reticular formation and nucleus centrum medianum, often showed independent driving characteristics (see fast record, Fig. 4, *B*).

It may be pointed out that the amount of driving occurring at the shaker frequency, particularly in subcortical structures, such as the midbrain reticular formation and nucleus centrum medianum, appeared to augment during changes in orientation of the head, as indicated by changes in the accelerometer readings from the head (Fig. 4). This was a frequent but by no means invariable concomitant of head movement. The possible significance of this finding in relation to the sensory receptor mechanisms responsible for the initiation of the EEG driving will be discussed below.

The records during shaking shown in Fig. 4 may be compared with the much more restricted distribution of driving in the same animal during photic stimulation (Fig. 3), and the virtual absence of driving in either cortical or subcortical leads from the same animal during shaking under pentobarbital anesthesia (Fig. 2).

In spectral sweeps from 5–40 c/sec, very little driving was seen until the shaking frequency was raised to 9 c/sec. It was uniformly found that driving in the EEG record was maximal between 9 and 15 c/sec, with a peak at 10–11 c/sec (Fig. 5, *A*). Accelerometer readings from the torso (Fig. 5, *A*, TORSO ACCEL.) indicated a resonance effect in the trunk at these frequencies, but this resonance was not reflected in simultaneous accelerometer readings from the head (HEAD ACCEL.). As in other records, the driving was particularly obvious in nucleus centrum medianum (L.C.M.) and the midbrain reticular formation (L.MB.R.F.). Intermittent driving was also noted in visual cortex, amygdala

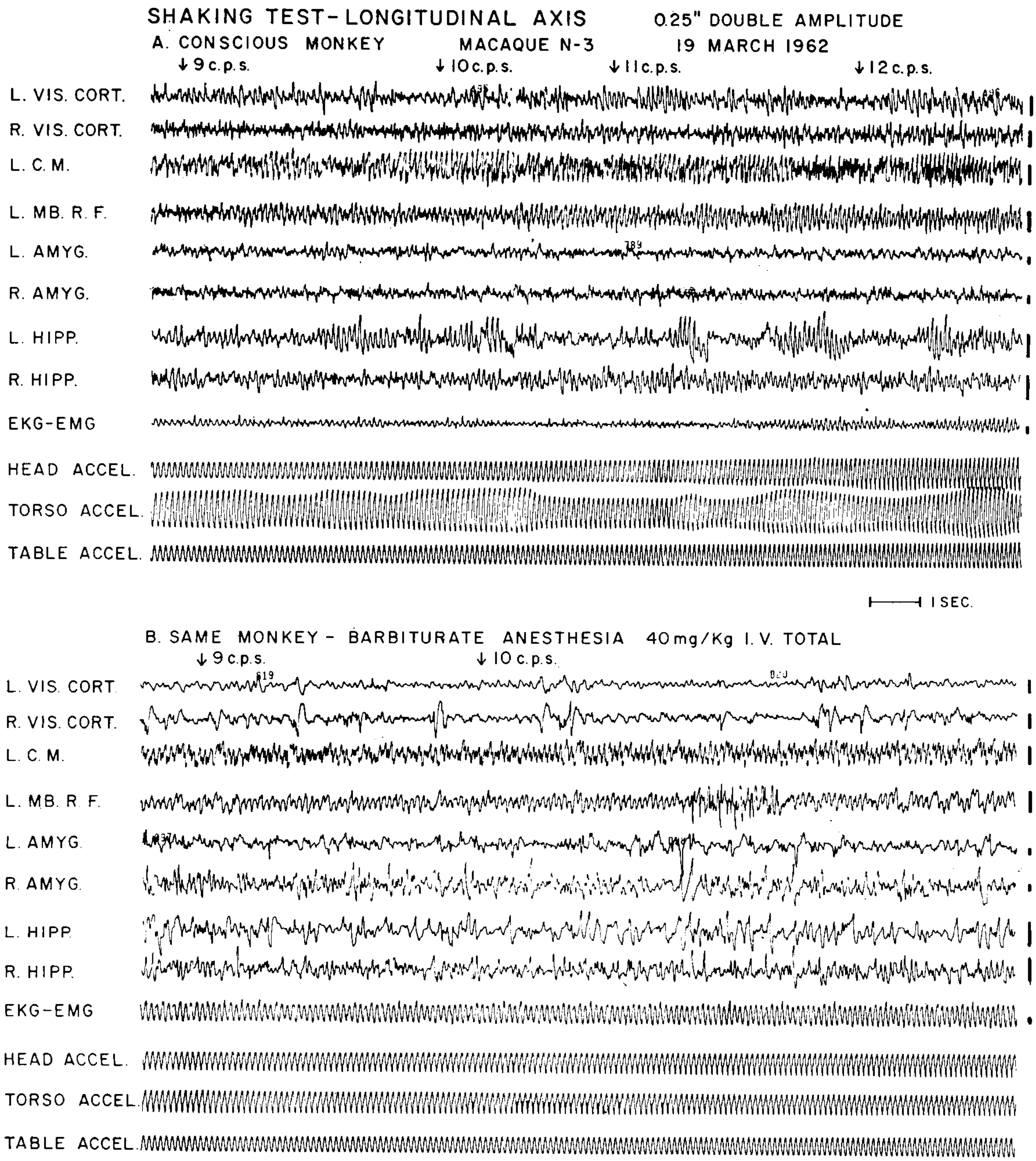

Fig. 5

Driving of EEG rhythms by shaking from 9–13 c/sec as part of spectral sweep. By contrast with records from conscious animal (*A*), records in (*B*) during pentobarbital anesthesia (40 mg/kg i.v.) show essentially no driving in hippocampal (L.HIPP. AND R.HIPP.) and visual cortical leads (L.VIS.CORT. AND R.VIS.CORT.). Driving in centrum medianum (L.C.M.) and midbrain reticular formation (L.MB.R.F.) was considerably reduced. Other lead abbreviations as in Fig. 2. Calibration 50 μV.

and hippocampus. A clear reduction in the amplitude of the driven activity occurred under pentobarbital anesthesia (Fig. 5, *B*) in nucleus centrum medianum and midbrain reticular formation, and a marked decline occurred in the visual cortex and hippocampal system.

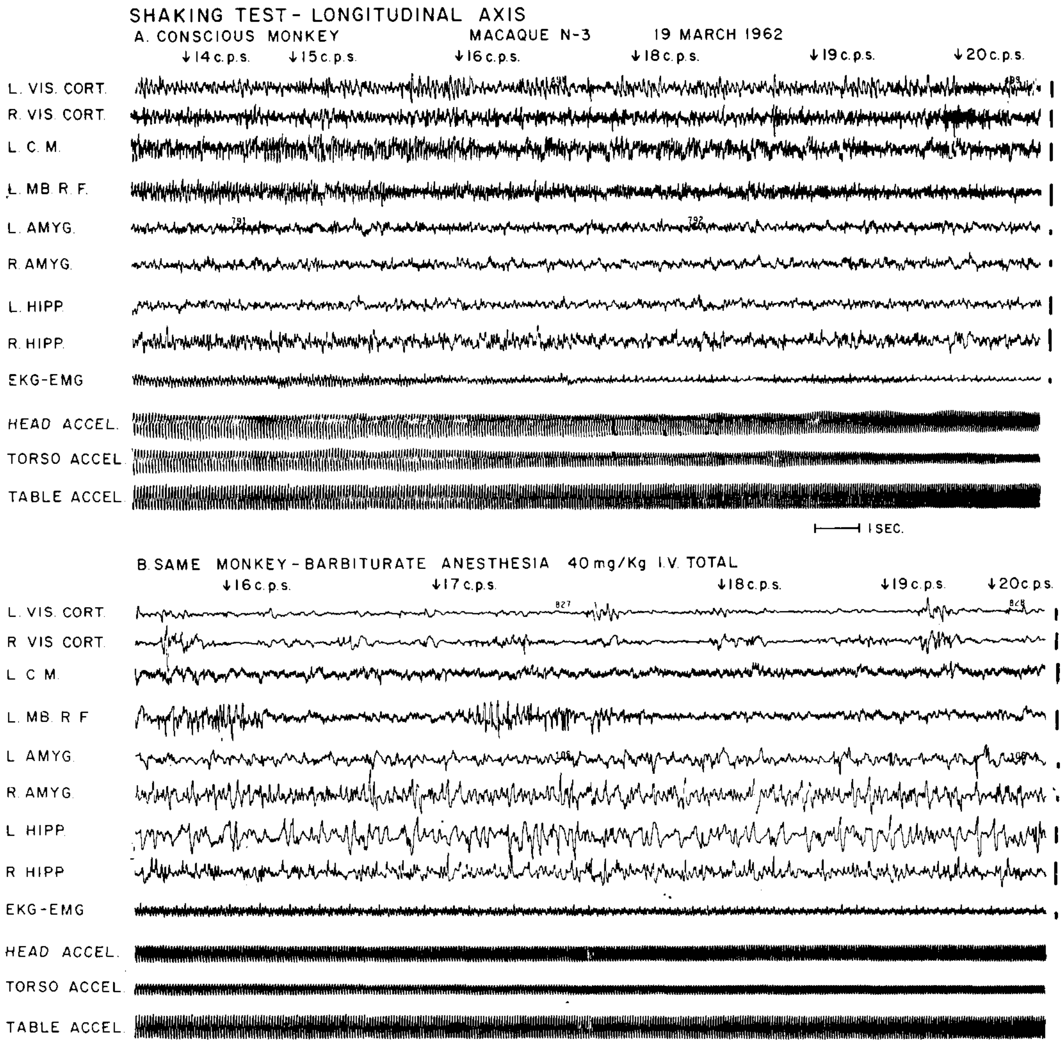

Fig. 6

Continuation of spectral sweep shown in Fig. 5. Driving of EEG rhythms fell progressively at shaking frequencies higher than 16 c/sec in both cortical and subcortical leads in conscious animal (*A*). With 16 c/sec shaking, rhythmic activity in left visual cortex occurred at half the shaking frequency. In the same animal (*B*) under pentobarbital anesthesia (40 mg/kg i.v.), no appreciable driving was present in cortical or subcortical leads. Lead abbreviations as in Fig. 2. Calibration 50 μV.

At higher frequencies (Fig. 6, *A*), driving persisted strongly in the band from 14–16 c/sec in visual cortex, hippocampus, centrum medianum and midbrain reticular formation, but declined progressively as the shaking frequency approached 20 c/sec. Appreciable driving at the shaking frequency was not usually seen beyond 20 c/sec. As noted in previous studies (Adey *et al.* 1961a), shaking at frequencies faster than 16 c/sec was sometimes associated with driving at half the shaking frequency. This can be seen in the visual cortex. (Fig. 6, *A*, L.VIS.CORT.) in the shaking range from 16—19 c/sec. The disappearance of virtually all driving in cortical and subcortical leads under pentobarbital anesthesia (Fig. 6, *B*) again confirms the hypothesis that the EEG driving arises in physiological processes, rather than electromechanical artifacts.

No evidence was found that the axis of shaking in any way determined the amount of driving or modified the critical frequencies for maximal driving. In summary, the driving phenomenon appeared to be frequency dependent.

C. *Induction of behavioral changes during vibrational stresses*

Each of the monkeys subjected to shaking was trained in an oddity discrimination task, as described above, in order to receive a food pellet reward. Details of EEG changes in the course of the discriminative judgment in the cat have been subjected to computer analysis, as already

TABLE I

Effects of vibration on oddity discrimination

Monkey	Date	Test No. trials	%Correct	Latency of correct responses (sec)
N3	3-26-62	Control(1)41	100	0.8
	3-29-62	Sham Run(2)23	65	8.5
	3-29-62	Vibration 59	44	4.3
N3	4-27-62	Control(1)40	100	0.8
	4-26-62	Sham Run(2)14	79	0.8
	4-26-62	Vibration 41	76	2.3
N4	4-27-62	Control(1)40	100	2.1
	4-26-62	Sham Run(2)15	100	1.4
	4-26-62	Vibration 26	97	2.0
N5	4-30-62	Control(1)40	100	1.3
	4-26-62	Sham Run(2)19	68	3.5
	4-26-62	Vibration 33	46	4.8

(1) Control test performed in laboratory test cage.
(2) Sham run-animal on couch on shaker, without vibration.

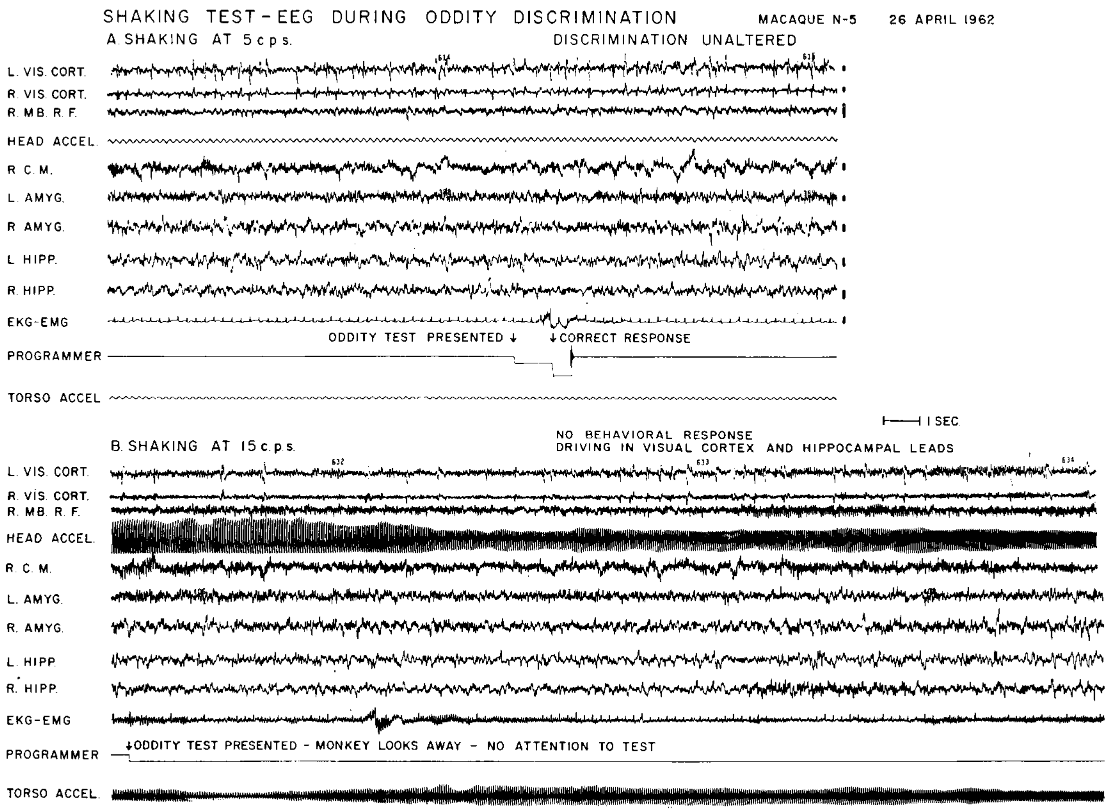

Fig. 7

Effects of shaking on EEG and concurrent oddity discrimination performance. Shaking at 5 c/sec (*A*) was without effect on EEG or behavioral performance. Shaking at 15 c/sec (*B*) was accompanied by EEG driving and the animal paid no attention to the task. Lead abbreviations as in Fig. 2. Calibration 100 μV.

followed by a rapid correct response. It may be emphasized that these animals were very highly trained, with less than 1 per cent errors in control tests in their laboratory cages. The findings in control tests in the laboratory test cage, and in sham runs without vibration but with the animal on the shaker table, and during vibration are summarized in Table I. It will be seen that the vibration was clearly associated with a decrement in performance and increased latency of response in two of the three animals tested.

D. *Seizure activity in the course of shaking tests*

No electrical or clinical manifestations of seizure discharges were detected in any shaking tests in the conscious animal. However, on one occasion, in shaking under complete but light general anesthesia with pentobarbital (35 mg/kg, i.p.), clinical seizures occurred, accompanied by a cry and jerking of the limbs (Fig. 9). These seizures occurred repeatedly at shaking frequencies between 25 and 35 c/sec. No EEG driving was noted in the epoch preceding the onset of seizures, which were accompanied by high amplitude slow waves in the range 2–5 c/sec. The motor concomitants of the seizure are clearly visible in the accelerometer records from the head.

E. *Sequelae to shaking stresses*

A careful check has been kept for both immediate and long-term sequelae of these episodes of mechanical stress. Continuous EEG records for periods up to 24 h after shaking have failed to disclose the persistence of any abnormality following these tests. The EEG records have resumed their pre-test character immediately after the end of shaking, and have remained unaltered. No neurological or behavioral abnormalities have been seen in monkeys followed for more than two years after more severe shaking (up to 4.5 *G* peak acceleration) than that used here (Adey *et al.* 1961a).

We have examined the electrode tracks in the brains of cats and monkeys subjected to both centrifuging and shaking. Many aspects of these findings have been described elsewhere (Winters *et al.* 1962; Adey 1961b), and have indicated that the implantation of the electrodes is not associated with a glial reaction greater than that seen in control animals not subjected to centrifuging or shaking. In the one animal of the present series sacrificed to provide a shaking record after death, glial scarring around the deeper parts of the electrode tracks was slightly thicker at levels 5–10 mm above the tip than at the tip itself. The glial reaction varied in thickness from 100–300 μ, and was thus not greatly in excess of the findings in non-accelerated brains (Fig. 10).

F. *Developments in electrophysiological recording techniques for space flight*

In the course of these studies, certain developments in amplifying techniques have been necessary, not only for possible animal experiments in the space environment, but also to provide at least a tentative basis for the application of the EEG as a most valuable monitor in manned space flight. The term "monitor" is used here in the connotation of astronautic jargon, in that it may be expected to provide information vital to the assessment of performance capability, and that it might therefore be available by telemetry under specified circumstances as "on-line" information.

We have developed microminiaturized EEG pre-amplifiers for manned space flight in a number of configurations. One, in the form of a small "top-hat" (Fig. 11), can be attached to the scalp by a simple sealing process with adhesives and can provide clean recordings for at least 24 h. Scalp contact is made through a moistened sponge, and a pair of such electrode-amplifiers connected to a differential main amplifier provide an in-phase rejection between 3,000 and 10,000 to 1. The total absence of a high impedance input lead and the low output impedance to the main amplifier (1,000 ohms) makes this device singularly resistant to interference induced from neighboring electrical noise sources, and to "sway artifacts" in connecting cables.

The top-hat configuration, although having great utility, does require fixation to the scalp, and its height, though small, may make it less convenient to apply and use within the confines of an astronaut's helmet and crushable liner. For these reasons we have pursued the philosophy of developing a system which can be put on and removed by the astronaut in the course of donning and removing his helmet, without any special attachment to the scalp, or parting of the hair, or removal of hair. The system shown in Fig. 11 appears quite promising. Pre-amplifiers in the form of small cylinders were embedded in the helmet liner. A short input lead of antistatic cable makes connection with a stainless steel wire, which, in turn, contacts a wick soaked in a non-irritating electrolyte. A silicon rubber grommet was moulded to fit an aperture in the liner and preserved the liquid content of the wick over many hours.

It was found that when the liner was placed

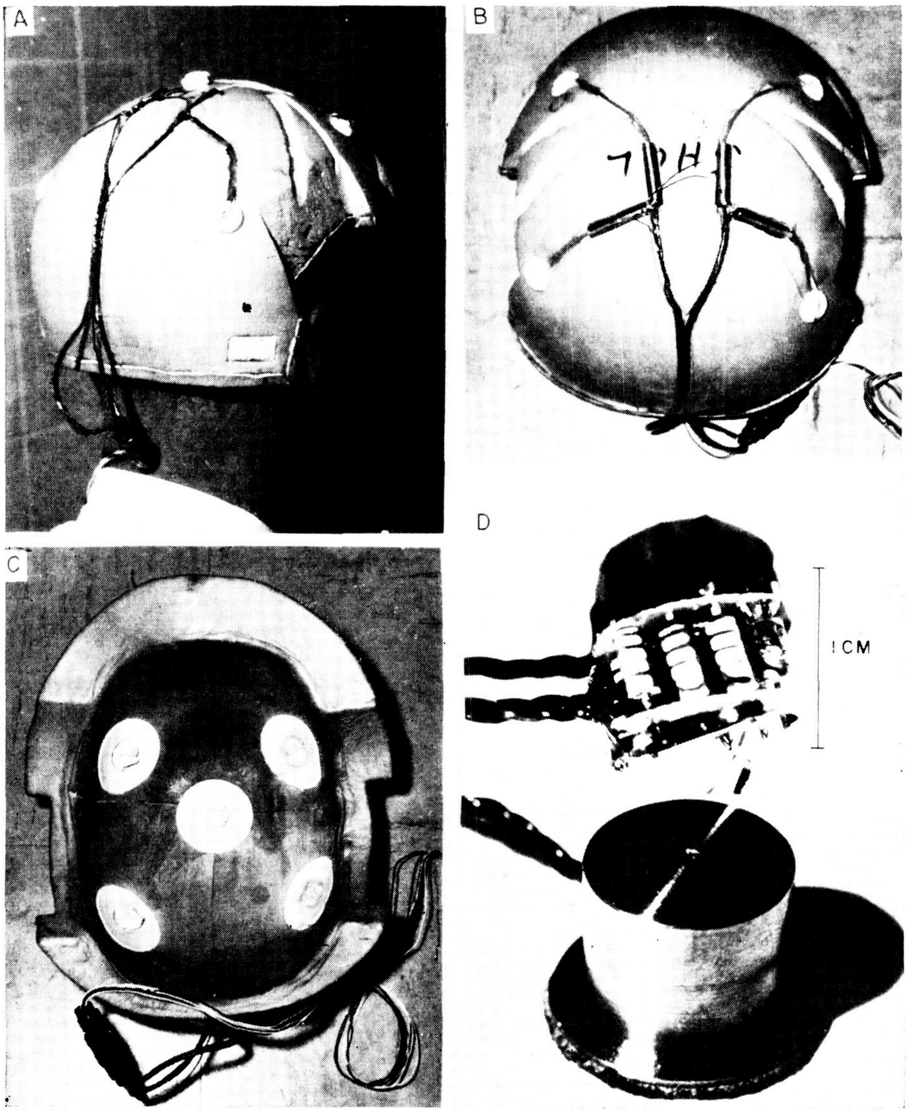

Fig. 11
Developments in amplifying techniques for EEG in manned space flight. Helmet liner of crushable material has been grooved to accommodate microminiaturized pre-amplifiers, constructed as small cylinders (*A* and *B*). Satisfactory scalp records can be secured for many hours by sponge electrode system retained in helmet liner by silicon rubber flanges, and without special preparation of the scalp (*C*). A different pre-amplifer configuration has been constructed inside a stainless steel "top-hat" with provision for direct attachment to the scalp and EEG pickup through a sponge electrode in its base (*D*).

on the head, without any preparatory cleansing of the scalp, a satisfactory contact developed within a few minutes. The contact developed more rapidly if electrode paste was lightly applied to the scalp but this was not essential. Particular attention was directed to the virtual elimination of the blocking characteristic of the amplifier, so that a sudden turning of the head within the liner produced no more than a very brief transient, with immediate restoration of the EEG tracing, using a low frequency band pass to 2 c/sec. Although this system must be regarded as preliminary at this time, it would appear to point the way to a useful simplification of the manifold difficulties of applying EEG to manned space flight on a "non-interference" basis.

DISCUSSION

It is obviously a matter of considerable importance in the assessment of EEG changes under conditions of severe physical stresses, such as centrifuging and vibration, to ensure that the physical stresses themselves do not produce artifacts which obscure or conceal the true nature of the induced changes in the physiological systems under test. For these reasons, we have exercised particular caution in ascribing to the brain itself only those phenomena which disappeared or were greatly modified in identical shaking tests conducted under anesthesia or after death. To achieve such an unequivocal differentiation, particular attention has been directed to elimination of artifacts which so commonly arise in connecting cables and lead connections, and in the present study, from possible leakage of either A.C. or steady magnetic fields associated with the operation of the shaking transducer.

On the basis of the available evidence, it appears that vibrational stimulation may produce a driving of EEG rhythms at certain relatively narrow bands of shaking frequencies. The phenomenon is reminiscent of photic driving, but our results indicate that it is independent of it. Apparently not all sensory modalities are capable of inducing a widespread rhythmic driving of cerebral electrical activity, even when the modality is activated at rates related to intrinsic cerebral rhythms. Grey Walter (1950) examined aspects of this problem, following his successful introduction of photic stimulation, and noted that rhythmic auditory stimulation appeared incapable of inducing driving of cerebral rhythms.

The question thus arises as to the modalities which may be involved in the driving seen here. Obviously, shaking of the whole body can produce tremendous influxes from the proprioceptive receptors in joints and muscles, and shaking of the head which may be expected to stimulate vestibular component may be involved. On the other hand, a mechanical resonance was clearly indicated in accelerometer readings from the torso at about 11 c/sec, so that susceptibility to driving in the vicinity of this frequency may indicate a relationship to volleys arising in thoraco-abdominal mechanoreceptors. It is of interest that Molnar (1961) has found vestibular stimulation, and the ensuing cerebral dysrhythmias, useful in the evaluation of certain forms of epilepsy. The possible interplay of spinal and vestibular influxes in the determination of reticular excitability has been discussed by Gernandt and Gilmans (1960).

In a more speculative vein, there remains the possibility that the driving might arise directly from mechanical effects in brain tissue. It is at least a theoretical possibility that such factors as intracranial pressure gradients, distortion of brain tissue, and altered dynamics of fluid movement may play a part. As discussed elsewhere, glial tissue may play a part in modulating neuronal excitability (Adey *et al.* 1962), and may be susceptible to mechanical distortion.

This account is devoted mainly to a certain facet of our studies of EEG applications in the space environment. Vibration will, after all, be confined to relatively brief phases of space journeys of increasing length and complexity. In broader perspective, EEG recording may be expected to achieve a significantly wider role in those longer journeys where the onset of fatigue, incipient sleep, and the assessment of sleep-wakefulness cycles, states of alerting and emotional perturbation may be vitally important in the evaluation of continued performance capability and, indeed, of survival itself. The feasibility of EEG recording in the cockpit environment has been tested by Sem-Jacobsen (1959). At least as important as the essentially pragmatic problem of evaluation of performance capability of man in space will be the vast wealth of fundamentally new knowledge of the brain as a functioning organ, which we may expect from experiments as unique in design as the space environment in which they will be conducted.

SUMMARY

17729

The effects of shaking on the electrical brain activity as recorded in cortical and subcortical structures of four pig-tailed macaques (*Macaca nemestrina*) are described.

Shaking was performed over a continuous spectrum from 5–40 c/sec, at a peak acceleration of 2 *G* over the greater part of the spectrum. Driving of brain rhythms at the shaking frequency was noted in the midbrain reticular formation, the nucleus centrum medianum, the visual cortex and the hippocampal system. An essentially different distribution of driving was produced by photic stimulation.

Control procedures indicated that this rhythmic driving was abolished or greatly reduced by pentobarbital anesthesia in both cortical and subcortical structures. It did not arise through sway artifacts in recording leads nor was it due to magnetic flux leakage in the vicinity of the shaking transducer.

The driving was maximal in the frequency range from 9–15 c/sec. At frequencies from 15–20 c/sec, evidence was found of driving at half the shaking frequency. The driving was frequently dissociated in simultaneous records from adjacent brain structures, and from leads in symmetric bilateral placements.

Concurrent behavioral performance in an oddity-discrimination test indicated an increase in errors, lack of attention and longer latency of responses at shaking frequencies around 11 c/sec, associated with maximal rhythmic EEG driving. An isolated instance of seizure induction during shaking under pentobarbital anesthesia is described.

Special requirements for EEG recording in manned space flight are discussed.

These studies have been supported by the U.S. Air Force Office of Scientific Research under Grant Number AF-AFOSR-61-81 and by a grant from the National Aeronautics and Space Administration. It is a pleasure to acknowledge the generous assistance of Douglas Aircraft Corporation, Santa Monica, California in the performance of the shaking tests. Centrifuging tests were performed through the continuing collaboration of Dr. J. P. Meehan and the Staff of the Department of Physiology, University of Southern California. Miss Cora Rucker and Miss Arlene Koithan have performed all histological examinations.

REFERENCES

Adey, W. R. Aspects of brain physiology in the space environment. In Symposium, *Brain Functions and Space, 1. Cortical Excitability.* Brain Research Institute, University of California at Los Angeles, **1961**a, in press.

Adey, W. R. Use of correlation analysis in EEG studies of conditioning. "Computer Techniques in EEG Analysis", M. A. B. Brazier (Editor). *Electroenceph. clin. Neurophysiol.*, **1961**b, *Suppl. 20*: 41–45.

Adey, W. R. Is there a need for a manned space laboratory? In *Lunar exploration and spacecraft systems.* Plenum Press, New York, **1962**a, ref. p. 170–177.

Adey, W. R. Potential for telemetry in the recording of brain waves from animals and men exposed to the stresses of space flight. In Symposium, *The Use of Telemetry in Animal Behavior and Physiology.* American Museum of National History, New York, **1962**b, in press.

Adey, W. R., Bell, F. R. and Dennis, B. J. Effects of LSD, Psilocybin and Psilocin on temporal lobe EEG patterns and learned behavior in the cat. *Neurology*, **1962**, in press.

Adey, W. R., Dunlop, C. W. and Hendrix, C. E. Hippocampal slow waves; distribution and phase relations in the course of approach learning. *Arch. Neurol. (Chic.)*, **1960**, *3*: 74–90.

Adey, W. R., French, J. D., Kado, R. T., Lindsley D. F., Walter, D. O., Wendt, R. and Winters, W. D. EEG records from cortical and deep brain structures during centrifugal and vibrational accelerations in cats and monkeys. *Inst. Radio Eng. Trans. Biomed. Electronics*, **1961**a, BME *8*: 182–188.

Adey, W. R., Kado, R. T. and Didio, J. Impedance measurements in the brain tissue of chronic animals, using microvolt signals. *Exper. Neurol.*, **1962**, *5*: 47–66.

Adey, W. R., Walter, D. O. and Hendrix, C. E. Computer techniques in correlation and spectral analyses of cerebral slow waves during discriminative behavior. *Exper. Neurol.*, **1961**b, *3*: 501–524.

Gernandt, B. E. and Gilmans, S. Vestibular and propriospinal interactions and protracted spinal inhibition by brainstem activation. *J. Neurophysiol.*, **1960**, *23*: 269–287.

Glenn, J. H. Pilot's flight report. In "*Results of the First United States Manned Orbital Space Flight*". National Aeronautics and Space Administration, Washington, D. C., **1962**, p. 119–136.

Graybiel, A., Guedry, F. E., Johnson, W. H. and Kennedy, R. S. Adaptation to bizarre stimulation of the semicircular canals as indicated by the oculogyral illusion. *Aerospace Med.*, **1961**, *32*: 321–327.

HENRY, J. P. Bioinstrumentation in Mr-3 flight. In "*Results of the First United States Manned Suborbital Space Flight*". National Aeronautics and Space Administration, Washington, D. C., **1961**, p. 37–44.

KADO, R. T. and ADEY, W. R. A transistorized preamplifier for field study of EEG. *Proc. 4th Internat. Conf. Med. Electronics*, New York, **1961**, p. 172.

LINDSLEY, D. F., WENDT, R. H., FUGETT, R., LINDSLEY, D. B. and ADEY, W. R. Diurnal cycles in monkeys under prolonged visual-pattern deprivation. *J. comp. physiol. Psychol.*, **1962**, in press.

MOLNAR, L. Effet de la stimulation du labyrinthe sur l'activité électrique normale et pathologique de l'écorce cérébrale du chat et de l'homme. *Actualités neurophysiol.*, **1961**, *3*: 61–82.

SEM-JACOBSEN, C. W. Electroencephalographic study of pilot stresses in flight. *Aerospace Med.*, **1959**, *30*: 797–801.

SHEPARD, A. H. Pilot's flight report. In "*Results of the First United States Manned Suborbital Space Flight*". National Aeronautics and Space Administration, Washington, D. C., **1961**, p. 69–75.

WALTER, W. G. The functions of electrical rhythms in the brain. *J. ment. Sci.*, **1950**, *96*: 1–31.

WINTERS, W. D., KADO, R. T. and ADEY, W. R. Neurophysiological aspects of space flight. In Symposium, *Lunar Flight*, American Astronautical Society, Denver, **1962**, in press.

Reference: ADEY, W. R., WINTERS, W. D., KADO, R. T. AND DELUCCHI, M. R. EEG in simulated stresses of space flight with special reference to problems of vibration. *Electroenceph. clin. Neurophysiol.*, **1963**, *15*: 305–320.